

Introduction to special section: Small-Scale Sea Ice Kinematics and Dynamics

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[1] Away from the ice margins, the response of the ice cover to large-scale gradients in atmospheric and oceanic forcing is concentrated along narrow zones of failure (up to tens of kilometers in width) resulting in openings, closings or shears. In winter, openings dominate the local brine production and heat exchange between the underlying ocean and the atmosphere. Convergence of the pack ice forces the ice to raft or pile up into pressure ridges and to be forced down into keels, increasing the ice-ocean and ice atmosphere drag. A combination of openings and closings is typical when irregular boundaries are sheared relative to one another. These processes shape the unique character of the thickness distribution of the ice cover and have profound impacts on the strength of the ice and its deformation properties over a wide range of temporal and spatial scales. Understanding the basin-scale mechanical character of the sea ice cover is thus of importance in modeling its behavior in a changing climate and in facilitating operational applications.

[2] In widely used models of sea ice, the representation of these processes is typically included in an aggregate and parameterized form based on simplifying assumptions. In the past, progress in model validation and improvements has been slowed by the lack of suitable observations. Except for focused field campaigns, observations of the above processes from buoy drift are limited by spatial sampling that is typically several hundred kilometers. Only with sea ice kinematics derived from high resolution Synthetic Aperture Radar (SAR) imagery have we been able to approach the spatial length scale required to observe these processes. In the late 1980s and most of the 1990s, the availability of small volumes of ice motion data from the European SAR satellites (ERS-1, 2) have allowed examination of sea ice strain rates at 5–10 km length scales and demonstrated the utility of these measurements for sea ice studies. However, the narrow swath of these early SAR missions obscures the spatial extent of the deformation patterns beyond ~100 km. Launched in November of 1996, the wide-swath coverage of the RADARSAT imaging radar offers a tool capable of providing high resolution

(~100 m) observations of the Arctic ice cover. Since 1997, routine 3-day RADARSAT data of the Arctic Ocean have been acquired and processed into imagery at the Alaska Satellite Facility. The NASA-funded RADARSAT Geophysical Processing System (RGPS) [Kwok, 1998], a joint project of the Alaska Satellite Facility and the Jet Propulsion Laboratory is a program for producing fine-scale sea ice motion products. The program objective is to provide a dataset suitable for understanding the basin-scale behavior of sea ice kinematics on a seasonal and inter-annual time scale, and for improving ice dynamics. Thus far, four winters and three summers of the RADARSAT acquisitions have been processed and the data products are posted at the following website: <http://www-radar.jpl.nasa.gov/rgps/working2/radarsat.html>.

[3] The availability of ice motion data from the RGPS program has allowed a more detailed and unprecedented look at the small-scale time-varying deformation of the ice cover [Kwok, 2001]. The RGPS observations point to the importance of understanding the consequence of ice pack as an anisotropic material with large-scale oriented fracture patterns. With the increasing resolution of coupled ice-ocean models that approaches the widths of leads, high resolution observations like that of the RGPS are needed for model development and validation. Simulation results can now be examined in detail. For climate studies, the impact of an anisotropic ice cover on surface heat and mass balance is not well understood. The RGPS dataset is a crucial component in the testing of new models that accounts for the spatial and temporal characteristics of these patterns.

[4] At the 2004 RGPS Science Working Group meeting in Seattle, the participants showed that there were sufficient potential papers and new results to justify a *Journal of Geophysical Research* special section to showcase recent work on this topic. They highlight the importance of high-resolution satellite observations for sea ice studies. There are also, of course, other papers that discuss these topics in other issues of *JGR*, as well as other journals. We encourage interested readers to examine these sources. The resulting collection is a special section that contains a mix of eight papers addressing a range of topics in modeling and observations of small-scale kinematics and dynamics of the sea ice cover: five papers address the issues of small-scale modeling, and three summarize the laboratory, in situ and satellite observations that describe the small-scale behavior of the sea ice cover.

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[5] Based on data provided by the RGPS and field measurements, *Coon et al.* [2006] revisit the AIDJEX (Arctic Ice Dynamics Joint EXperiment) assumptions about pack ice behavior and provide a new view that necessitates the direct modeling of velocity (displacement) discontinuities. They argue that the anisotropic sea ice cover with oriented discontinuities is inadequately represented in current models in terms of lead and ridge formation, and that this consideration becomes even more important as models approach the 10 km scale. With this motivation, *Schreyer et al.* [2006] propose an elastic-decohesive constitutive model for sea ice with the specific purpose of modeling when a lead is initiated and to provide the resultant orientation, mode of failure, and lead width. This approach is different from the more common procedure of using a continuum constitutive equation with a failure criterion to simulate leads, or from modeling the complete ice pack as discrete floes. *Sulsky et al.* [2006] demonstrate that the material-point method (MPM) could be used to provide solutions for both the viscous-plastic and the elastic-decohesive constitutive laws. This method provides a Lagrangian system that advects with the ice cover. Properties such as ice thickness and compactness computed in this Lagrangian frame do not suffer from errors associated with Eulerian advection schemes, such as artificial diffusion, dispersion, or oscillations near discontinuities.

[6] Numerical instability in many high-resolution (~ 10 km) sea ice models is addressed by *Lipscomb et al.* [2006]. They show that a feedback between the standard sea ice ridging scheme and viscous-plastic dynamics can cause instability. This instability generally arises when large strength gradients lead to excessive convergence and divergence, amplifying these gradients. A key to numerical stability is to reduce the strength differences between neighboring grid cells.

[7] *Hopkins and Thorndike* [2006] use a granular model of the central Arctic ice pack to show that the Arctic pack may have a wide distribution rather than a near-uniform distribution of floe sizes characteristic of a fine-grained granular material. The model consists of thousands of individual grains that can freeze together, fracture apart, and interact through ridging. Their simulation results argue for a continual quasi-steady process of fracture and freezing leading to a distribution of floe sizes in equilibrium with thermal and mechanical forcing and underlines the importance of the fracture process in creating the small-scale deformational structure of the pack.

[8] At the laboratory scale, *Schulson et al.* [2006] construct the brittle failure envelope of harvested first-year Arctic sea ice using laboratory mechanical experiments. Brittle behavior of sea ice is expressed in the ubiquitous fractures of the ice cover, as manifested by cracks, pressure ridges and rubble fields, and quite remarkably by strike-slip type oriented linear kinematic features that can run hundreds to thousands of kilometers through the winter cover. The authors also hold that although the Arctic Ocean is a more complicated arena than the laboratory, the fundamental

processes through which sea ice fails are probably scale-independent.

[9] In the marginal ice zone, *Doble and Wadhams* [2006] compare the dynamics of pancake ice before and after consolidation using an array of drifting buoys in the Weddell Sea. Drift velocities are higher, and strain rates display amplitude, frequency oscillations in the unconsolidated ice that are up to two orders of magnitude higher than normally reported for the Weddell Sea pack ice. The observations suggest major implications for model rheologies, surface heat fluxes and hence ice growth and brine rejection to the ocean.

[10] Using four years of RGPS data, *Kwok* [2006] summarizes the ice deformation and production in the seasonal (SIZ) and perennial (PIZ) ice zones of the Arctic. Ice deformation is higher in the SIZ with correspondingly higher deformation-related ice production that is 1.5–2.3 times that of the PIZ. He suggests that the deformation-ice production relationship alone could be considered a negative feedback when thickness is perturbed, but in the overall scheme other forcings should be considered.

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